DESIGN OPTIONS FOR A PULSED-POWER UPGRADE OF THE Z ACCELERATOR*

K. W. Struve, J. P. Corley, D. L. Johnson,+ H. C. Harjes, D. H. McDaniel, R.W. Shoup,++
D. L. Smith, W. A. Stygar, and E. A. Weinbrecht, Sandia National Laboratories,
P.O. Box 5800, MS1194, Albuquerque, NM USA, 87185

Abstract

We are presently considering an extensive modification of the Z accelerator at the Sandia National Laboratories to both increase the current and radiative power, and to improve the facility, diagnostics, and shot rate. Record-breaking peak x-ray powers and Hohlraum temperatures achieved in z-pinch experiments on this machine motivate this effort. The electrical design goal of the upgrade is to drive a 40-mm diameter, 20-mm long wire-array z-pinch load with a peak current of 26 MA with a 100-ns implosion. Several changes to the pulsed-power design of Z are being considered. They are to increase the energy and lower the inductance of the Marx bank, increase the capacitance of the intermediate-store water capacitor, increase the voltage hold-off capability of the laser-triggered gas switch, lengthen the first section of the water pulse-forming line, remove impedance mismatches in the pulse-forming line, and adjust field grading on the water side of the insulator stack. With these changes Z will be able to provide peak currents greater than 26 MA, and x-ray energies exceeding 2.7 MJ. We plan to use the existing oil and water tanks, use the existing insulator stack and MITL's, and as much of the existing Marx-bank hardware as feasible. Circuit-code calculations for one design option are shown. The results of these simulations, when applied to standard water-breakdown criteria, are used to determine the size of the intermediate store (IS) and pulse-forming-line (PFL) components. We also indicate where further component development is needed.

I. Design Requirements

The upgrade to the Z accelerator, which is to be called ZR, which is an acronym for Z refurbishment, is meant to increase precision and reliability, number of shots per year, and radiation power output from the z pinch. The specific requirements are listed in Table 1. The abbreviations in the table are VH for vacuum *hohlraum*, DH for dynamic *hohlraum*, and ICE for isentropic compression experiments. To achieve these goals both the accelerator and the supporting facilities will need to be improved. These will include upgrades to the building for air-temperature and air-particulate control, water-temperature control, larger over-head crane capacity, and upgrades to the machine and radiation diagnostics. The building and tank will not be increased in size.

Since the z-pinch load behaves as an inductor, to achieve the higher currents with the same current rise time, it is necessary to increase the drive voltage. Therefore, the approach to the design is to find a design that can increase the voltage to the load by roughly 50% within the existing tank structure.

Table 1. Design goals for ZR

Capability	Z today	ZR
Current into a 40 mm diameter, 20 mm long z-pinch	18 MA	26 MA
Current reproducibility	± 5 %	± 2 %
Pulse width	100 – 120 ns	100 – 120 ns
Power radiated (nested arrays)	230 TW	350 TW
Energy radiated (single array)	1.6 MJ	2.7 MJ
$T_{radiation}$ for weapons physics VH/DH	140 / 220 eV	165 / 260 eV
$T_{radiation}$ for ICF VH/DH	75 / 140 eV	90 / 165 eV
Peak pressure for ICE	3.5 Mbar	17 Mbar
Flyer-plate velocity	21 km/s	47 km/s
Radiation energy in band 1 keV / 5 keV / 8 keV	450 / 100 / 18 kJ	900 / 300 / 72 kJ
Shots per year capability	240 – 270	400 - 440
Pulse-shape tailoring, 250 – 300 ns long pulses	Limited	All lines

II. Design Options

Several options for the design of the upgraded accelerator have been considered. The most conservative is to modify and upgrade the existing Z design to handle the increased voltage and current. Another design that offers the possibility of lower switch voltages is a Blumlein design that uses a power doubler. The advantage of the doubler is that it reduces the hold-off voltage on the water switches in the pulse-forming line by

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+ Titan, Pulse Sciences Division, 600 McCormick Street, San Leandro, CA 94577, USA.

++ Defense Threat Reduction Agency (DTRA), 1680 Texas St. SE, Kirtland AFB, NM 87119-5669, USA.

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14. ABSTRACT
We are presently considering an extensive modification of the Z accelerator at the Sandia National Laboratories to both increase the current and radiative power, and to improve the facility, diagnostics, and shot rate. Recordbreaking peak x-ray powers and Hohlraum temperatures achieved in z-pinch experiments on this machine motivate this effort. The electrical design goal of the upgrade is to drive a 40-mm diameter, 20-mm long wire-array z-pinch load with a peak current of 26 MA with a 100-ns implosion. Several changes to the pulsed-power design of Z are being considered. They are to increase the energy and lower the inductance of the Marx bank, increase the capacitance of the intermediate-store water capacitor, increase the voltage hold-off capability of the lasertriggered gas switch, lengthen the first section of the water pulse-forming line, remove impedance mismatches in the pulse-forming line, and adjust field grading on the water side of the insulator stack. With these changes Z will be able to provide peak currents greater than 26 MA, and x-ray energies exceeding 2.7 MJ. We plan to use the existing oil and water tanks, use the existing insulator stack and MITLs, and as much of the existing Marx-bank hardware as feasible. Circuit-code calculations for one design option are shown. The results of these simulations, when applied to standard water-breakdown criteria, are used to determine the size of the intermediate store (IS) and pulse-forming-line (PFL) components. We also indicate where further component development is needed.

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almost a factor of two. But a potential problem is that the Blumlein must be nearly 3 m (10') in diameter.

A stacked Blumlein design is also being considered. It offers improved utilization of the water volume in the Z tank. It also has less demanding requirements on the switches. But it does have difficulty with providing long pulses lengths needed for the ICE experiments. This technique also needs to be tested experimentally. It is unlikely that this approach will be sufficiently developed before a design decision will need to be made.

Water and cavity adders have also been considered. With both of these approaches lower voltage components are used, and the higher voltage is achieved by adding the outputs with either inductive adders, or by using transit-time isolation. Because both of these techniques require doubling the number of pulsed-power components, it is generally thought that it will not be possible to fit these designs into the available space at Z.

Another very-promising approach is to use the fast linear transformer driver (LTD) being developed by Kim and Kovalchuk.[1] With this approach the Marx bank and pulse forming is done in single cavities that are added inductively. A large advantage to this approach is that it is not necessary to locate these components in large water or oil tanks. Furthermore, the requirement for a large, high-voltage vacuum insulator is eliminated. Since only single-module tests of this technique have been done it is not likely that we can commit to this design before doing more development and testing with larger-scale devices.

The last option is to use lower-voltage, lower-impedance pulse-forming lines that drive a transmission-line transformer. Since this technique requires long transmission lines to avoid pulse distortion, it is not clear that there is space available in the Z tank for this technique. But with abrupt impedance transitions it may be possible to adapt the technique.

III. A Z-like Design Option

A likely approach to the ZR pulsed-power design is to increase the energy in the Marx bank, and to upgrade the voltage capability of the components in the existing design. The 1.3 μF, 100 kV capacitors in the Marx bank will be replaced with 2.6 μF capacitors with the same dimensions, and the number of capacitors will be increased from 60 to 72 by adding an additional row. This increases the Marx capacitance from 22 to 36 nF. With this change, the Marx capacitors will only need to be charged to ± 80 kV to deliver 26 MA to the z-pinch load.

The IS water capacitor will be increased from 16 to 24 nF, and its voltage hold-off capability increased from 4.8 MV to 5.5 MV. Its length will be increased to at least 110 ns to provide capability for a long-pulse mode of operation. The laser-triggered gas switch will also be lengthened and redesigned to allow operation up to 5.5 MV.

In the pulse-forming section the first water line (line one) will be lengthened from 35 to 50 ns to improve the drive efficiency for 100 ns implosions, and to provide more flexibility for using longer pulse lengths. It will need to hold off 5.6 MV before switching. The water switches at the output of this line will need to switch at 5.6 MV, whereas now they switch at 2.8 to 3.3 MV.

The water lines following the pulse-forming section are now 4.32 Ω, which is 0.12 Ω equivalent for the thirty-six lines of the entire machine. Efficiency calculations show that this impedance should be increased to 0.18 to 0.2 Ω. But for the simulations shown below the impedance is kept at 0.12 Ω.

Finally, the vacuum insulator stack and vacuum MITL inductance will be increased by approximately 11 % to reduce electron emission. Experiments have shown that the existing insulator can tolerate up to a 50 % higher voltage than it now experiences,[2] but electron flow in the vacuum MITLs could become a problem with the higher voltages. Therefore, vacuum flare and MITL-dimension adjustments are anticipated.

Circuit-code simulations using the SCREAMER code [3] have been done with these changes using a four-level model. Each level simulates nine lines of Z driving one level of the insulator stack. The simulation is divided in this manner since each level of the insulator stack has a different inductance. The simulation includes all of the components listed above, and includes losses in the gas switch, water switches, the pre-pulse suppression switches, and at the post-hole convolute near the load. It also includes the time-varying inductance of the z-pinch load. The Marx bank is assumed to be fully erected at the start of the simulation, and has a fixed series resistance of 4 Ω, and a series inductance of 13 μH. All water line and MITL components are modeled as transmission lines to correctly handle transit-time effects.

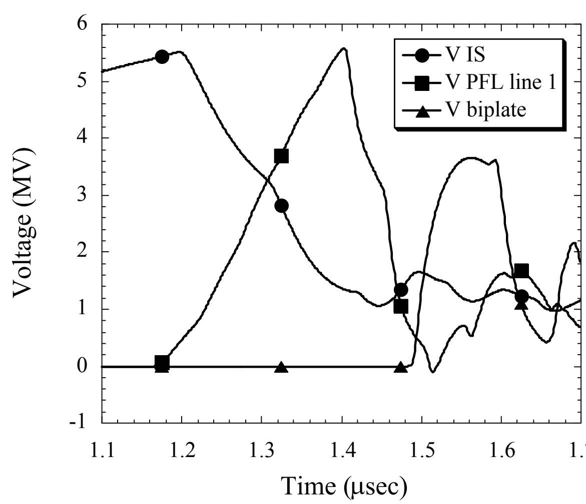

Figure 1. Screamer-predicted voltages in the IS, PFL, and biplate transmission lines.

The voltages predicted for the IS, the PFL line one, and the water-transmission line biplates are shown in fig. 1. Here the peak IS voltage is 5.52 MV. On line one it is 5.58 MV, and on the biplates it is 3.66 MV. The $t_{effective}$, the time the pulse is above 63% of peak, is 504, 84, and

96 ns at those three positions. The average electric field on each of the insulator stacks is shown in fig. 2 as a function of time. The field is calculated as the voltage across each insulator divided by the insulator height. The peak field is almost 150 kV/cm, which is nearly 50 % higher than presently seen on Z.

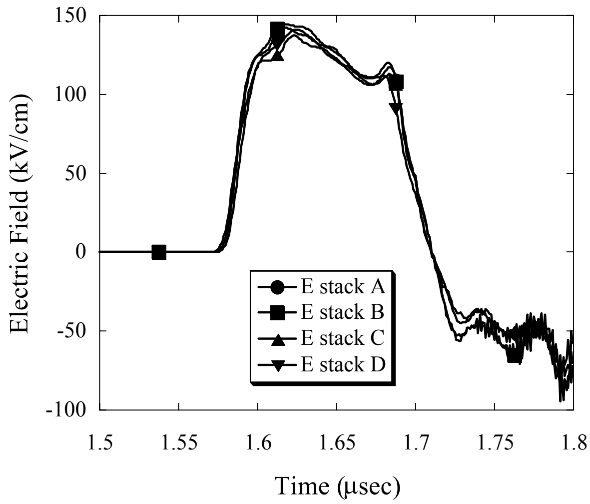

Figure 2. Electric field on the four levels of the stack.

The current and kinetic energy (KE) delivered to the baseline load, which is a 40 mm diameter, 20 mm long wire array with a 5 mm anode-cathode gap, is shown in fig. 3. The peak current is 26.7 MA, and the KE 2.4 MJ. Typically, the measured radiated energy exceeds the calculated KE by a factor 1.3. This can be understood by remembering that a large amount of energy is available for the pinch in the magnetic field surrounding the pinch. So this value corresponds to a radiated energy of 3.1 MJ.

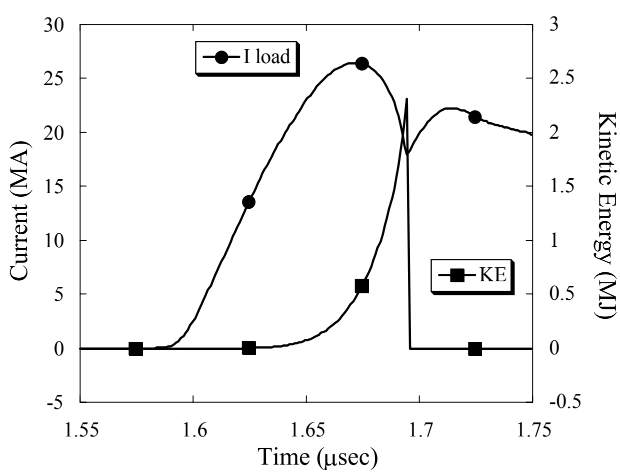

Figure 3. Load current and KE for the baseline load.

In addition to the baseline load, other loads can be considered with the upgraded design. A typical *hohlraum* load has a 20-mm diameter wire array that is 10 mm long, and has a 2.5-mm radial anode-cathode gap. Also considered is a double-wire-array *hohlraum* load that has two 10-mm-long, 20-mm-diameter wire arrays in series separated by a 10-mm long *hohlraum*. Also calculated are two short-circuit configurations. Both have ICE loads. One is for the normal, short-pulse mode. The other is with the line-one switches shorted to produce a 250-ns long pulse. The peak currents predicted for these loads are shown in table 2.

Table 2. Screamer-predicted currents, KE, and radiation for several load configurations.

Load Configuration	Peak Current (MA)	Kinetic Energy (MJ)	Radiated Energy (MJ)
Baseline load	26.7	2.4	3.1
Hohlraum load	28.0	1.7	2.3
Double-wire-array hohlraum	23.7	2.3	3.0
ICE load, 100 ns mode	34.0	-	-
ICE load, 250 ns mode	34.4	-	-

The biggest uncertainty in the simulations is with the predicted loss in the laser-triggered gas switch. A comparison of switch losses with recent measurements indicates that actual losses are less severe than modeled. Water-switch loss predicted by the simulations is much closer to empirically measured values. It can be approximated with a fixed resistance in the range of 35 to 90 mΩ per cm of gap length. The Screamer model uses a time-varying loss that is much higher just after switching that rapidly falls too much below this range.

The biggest concerns about the design are with the voltages required for the gas and the self-break water switches, and with jitter and pulse round off with the water switches. The water switch needs to operate at 5.6 MV, whereas today on Z it self-breaks at 3.3 MV with a 7-cm gap. Scaling the breakdown with a point-plane scaling [4], correcting for longer rise times and higher switch voltages, indicates that water-switch gaps may need to be as large as 18 cm. Experience from other machines is that significant jitter and pulse rounding is likely with large gaps at these voltages.[5] This problem will need to be resolved.

IV. Component Requirements

From the voltages from the simulations we can estimate the required sizes for the intermediate store and PFL line 1. This is done by using the JCM criteria, as applied to the anode (outer) conductor,[6] and by using a more-conservative point-plane water breakdown formula. The fraction f of breakdown from the JCM formula is expressed as

$$f = E\ t_{effective}^{1/3}\ A^{.058} \big/ 230\ , \qquad (1)$$

where E (kV/cm) is the peak electric field at the anode, A (cm^2) is the electrode area, and $t_{effective}$ is in µsec. Similarly, the fraction of breakdown from the point-plane formula is

$$f = E_{ave}\, t_{effective}^{1/2} \Big/ 100 \ . \qquad (2)$$

Here the E_{ave} is the average between the electrodes.

With the peak voltage and pulse width from the simulations we can estimate the fraction of breakdown for various IS and PFL diameters. Fraction of breakdown is shown in table 3 for a 110-ns long, 24 nF IS. A conservative design, which allows for operation with a 100 kV Marx-bank charge, requires an outer diameter of 2 m. The results of a similar calculation for the first line of the PFL are shown in table 4. This calculation assumes a 2.5 Ω, 50-ns long transmission line. A conservative design for this section will require an outer diameter of 1.7 m.

Table 3. Breakdown fraction
for a 24 nF, 110-ns long IS versus electrode diameter

Outer Conductor Diameter (m)	Inner Conductor Diameter (m)	Fraction of Breakdown, JCM, 80 kV	Fraction of Breakdown, point-plane, 80 kV	Fraction of Breakdown, JCM, 100 kV	Fraction of Breakdown, point-plane, 100 kV
1.52	0.77	0.90	1.03	1.13	1.29
1.68	0.84	0.83	0.94	1.03	1.18
1.83	0.92	0.76	0.86	0.95	1.08
1.98	1.00	0.71	0.80	0.88	0.99
2.13	1.07	0.66	0.74	0.82	0.92
2.29	1.15	0.62	0.69	0.77	0.86
2.44	1.23	0.58	0.65	0.73	0.81

Table 4. Breakdown fraction
for a 2.5 Ω, 50 ns long line 1 PFL

Outer Diameter (m)	Inner Diameter (m)	Fraction of Breakdown, JCM, 80 kV	Fraction of Breakdown, point-plane, 80 kV	Fraction of Breakdown, JCM, 100 kV	Fraction of Breakdown, point-plane, 100 kV
1.22	0.84	1.09	0.85	1.36	1.06
1.37	0.94	0.97	0.75	1.22	0.94
1.52	1.05	0.88	0.68	1.10	0.85
1.68	1.15	0.81	0.62	1.01	0.77
1.83	1.26	0.74	0.57	0.93	0.71
1.98	1.36	0.69	0.52	0.86	0.65
2.13	1.47	0.64	0.48	0.80	0.61

Other critical components are the laser-triggered gas switch, and the self-break water switches. With an 80-kV Marx charge, the switch will need to hold off 5.5 MV. But with a 100-kV charge it will need to hold 6.8 MV before switching. Similarly, the water switch will need to break at 5.6 MV with the nominal 80-kV charge, and 7.0 MV for the 100-kV charge.

Several approaches are being taken to address the higher switch voltages that will be required. One is to redesign our present switches by lengthening and adjusting the grading, and to test at the required voltages. We are now constructing a high-voltage test facility for testing switches in water, and have just completed a successful set of tests of a 6-MV gas switch in oil.

Another approach is to mismatch the circuit to reduce the voltage requirements on the switch. The mismatch results in a loss of efficiency, but with energy to spare in the Marx bank, we can trade efficiency for reduced stress on the switch.

V. Summary

Recent success with the Z accelerator has motivated upgrading the machine to improve its shot rate, precision and reproducibility, and radiation-power output. Several design options are being considered, but a for timely, cost-effective approach, an upgrade to the existing architecture is most likely. The energy in the Marx bank will be increased, and the voltage-holding capability of the PFL components are planned. Minimal changes will be made to the vacuum insulator stack and the vacuum MITL's. The size of the components in the oil and water sections is reasonable and can fit in the existing tanks. Of most concern are the voltage requirements on the gas and water switches. Efforts are be take to both increase the capabilities of existing designs, and to modify this preliminary design to reduce the voltage requirements.

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